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# RECENT RE-MEASUREMENT OF THE NEUTRON AND GAMMA-RAY FIELDS AT LARGE DISTANCES FROM A PROMPT CRITICAL FACILITY (U)

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REPORT NO.1031

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## ABSTRACT

Over the past few years the neutron (and to a lesser extent gamma-ray) energy spectra at the NATO standard reference point (400 m from the core) at the Aberdeen Pulsed Radiation Facility, Aberdeen Proving Ground, MD, US has been the subject of experimental and theoretical controversy. This report describes the Canadian results of a joint NATO spectroscopic and dosimetric program carried out to end the controversy. Free-field and in-vehicle spectra are given, along with free-field and phantom dosimetric results. As a result of this work, several benchmark results have now been obtained, and specific recommendations for future research are given.



## RÉSUMÉ

Depuis quelques années, le spectre d'énergie des neutrons, et dans une moindre mesure des rayon-gammas, mesuré au point de référence standard de l'OTAN (à 400m du coeur), des installations de recherche sur les radiations transistoires de Aberdeen a été sujet à controverse. Ce rapport décrit les résultats canadiens d'un programme conjoint avec l'OTAN de spectroscopie et de dosimétrie entrepris pour répondre à cette controverse. Les résultats des cette étude y sont décrit et quelques recommendations pour des recherches futures sont suggérées.

## EXECUTIVE SUMMARY

The need for accurate determination of the neutron and gamma-ray energy spectra, both free-field and in simulated vehicle, at the NATO standard reference point at Aberdeen Proving Ground (400 m from the critical facility) led to a joint NATO experimental program. The Canadian results, which are of benchmark quality, are presented here. As a result of these experiments, specific recommendations on spectroscopic and dosimetric procedures are given, including:

a. The use of a ROSPEC-based system for neutron spectroscopy in fission/degraded fission environments.

b. The use of a BGO spectrometer for gamma-ray measurements.

c. The use of the BD-100R "bubble" detector for neutron dosimetry.

d. The use of $CaF_2$:Mn thermoluminescent dosimeters for gamma-ray dosimetry, pending development of a more sensitive device.

e. The use of the BDS bubble spectrometer set for spectroscopy at highly localized positions.

f. The use of the RT-200 anthropomorphic phantom as a human simulator.

g. The need for further work on shielded environments such as in-vehicle, in-woods, etc.

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## 1. Introduction

As an ongoing research project over the past ten years various NATO laboratories have been making experimental measurements (1,2,3) and performing theoretical (4,5) calculations to define the neutron and gamma-ray energy spectra at various distance (up to ~ 1 km) from the critical facility at the Nuclear Efects Directorate, U.S. Army Aberdeen Proving Ground (APG), Md. These experiments have been concerned chiefly with the "NATO standard reference point" located at 400 m from the core.

The wide spread in measured free-field energy spectra (especially for neutrons) (6) has become a cause of concern over the past few years. Various hypotheses for the discrepancies among the measurements had been postulated - from the influence of meteorological parameters (5) to inconsistent calibration techniques. The need for agreement on these free-field spectra was addressed at the recent NATO RSG-5 (Panel VIII) Physical Dosimetry Sub-committee meeting (7) and the conclusion was that simultaneous measurement, using a variety of techniques, by all interested NATO members was the only way to resolve the dilemma.

As a result, a time frame of Oct 23 - Nov 3, 1989 was allocated at APG for collaborative experiments. Participants included ETCA (France), Aldermaston (UK), APG, ORNL, SAIC and DNA (US) as well as Canadian representation from DREO and BTI.

The Aberdeen experiments were not, however, restricted to exclusively free-field work. Spectroscopic and dosimetric measurements were also taken in the "NATO standard test bed" (8) (a 2m cubed box with 4 inch thick steel walls) - both free-field and on an anthropomorphic phantom. Finally, measurements were taken to examine the effect of the dense forest around the 400 m point on neutron and gamma-ray energy spectra. The results presented here summarize the Canadian results. Only brief mention of the others will be made for illustrative purposes.

## 2. Experimental:

### 2.1 Equipment

#### 2.1.1 Spectroscopy

For these experiments there were a total of three CA neutron spectroscopic systems employed. All have been used before by DREO. They were:

(i) The ROSPEC system (9), consisting of four hydrogen based proportional counters rotating about a common geometric centre. The efficiencies of the detectors are such that the energy range from 50 keV to 4.5 MeV may be spanned.

(ii) The NE213/$BF_3$ system (10). The NE213 spectrometer is used to span the range 0.6 MeV - 10 MeV. Extrapolation to lower energies relies on cadmium-

(ii) The NE213/$BF_3$ system (10). The NE213 spectrometer is used to span the range 0.6 MeV - 10 MeV. Extrapolation to lower energies relies on cadmium-covered and bare $BF_3$ counters to determine the thermal fluence, followed by a 1/E extrapolation up to 0.6 MeV.

(iii) The 'Bubble Spectrometer' (11). By varying the energy threshold of super-heated drop detectors, a crude spectrometer with six energy bins can be fabricated. The major advantage of this device are its small size, high efficiency and passive nature.

Gamma-ray Spectroscopy was achieved using a BGO spectrometer exclusively (12), owing to its superior energy resolution and efficiency over more conventional systems. The BGO spanned the energy range from 0.1 MeV to 12 MeV.

2.1.2 Dosimetry:

Only neutron dosimetry was attempted using the BD-100R bubble detector (13). This was due primarily to the lack of any complementary gamma-ray spectrometer with reasonably comparable efficiency.

2.2 Results:

2.2.1 Free-Field Spectroscopy

Fig (1) shows the free-field neutron energy spectra at the reference point as determined by ROSPEC and the NE213/$BF_3$ system. Note that over the energy range ~ 1 MeV to ~ 4 MeV the two spectra overlap reasonably well. However below 1 MeV the NE213 measured fluence is considerably lower than that measured by ROSPEC. As a consequence of this, the extrapolated NE213 fluence down to the $BF_3$ counts is also quite low.

The reason for the lower counts is apparently cross-over related and tends to raise the effective detector threshold from 0.6 MeV to ~ 1 MeV. This effect has been observed before, and DREO has offered a simplified solution (14). This method consists of matching the $BF_3$ counts to a 1/E spectrum intersecting the NE213 spectrum at 1 MeV (and thus rewriting the counts in the bins centered at 0.7 and 0.9 MeV). After performing these corrections the data now compare much more favourably, as shown in fig (2). It should be noted in passing that all NE213 systems (CA, FRA and US) employed in these experiments showed the same trends, i.e. an underestimate of the fluence below 1 MeV, and thus an underestimate of total kerma. Table (1) shows the measured kerma by energy intervals. Clearly the NE213 system is incapable of accurately measuring a degraded fission spectrum without appropriate corrections.

Another interesting feature for the comparisons is the structure observed by the NE213 around 2 MeV. This had, in the past, been attributed to

the large "neutron window" in the oxygen neutron-scattering cross-section (15). The window is quite deep and narrow. The fact that ROSPEC does not observe this structure is surprising, since it has superior energy resolution compared to NE213. Recent DREO experiments have shown similar structure in NE213 measured $^{252}Cf$ spectra (16), indicating that this peak is at least partially a detector artifact.

It is interesting to examine the structure observed by ROSPEC below 1 MeV (clearly the NE213/$BF_3$ system can never observe this due to the extrapolation procedure itself.) The peaks are due to neutron windows in nitrogen and oxygen and their locations have been predicted theoretically (5) as shown in fig (3). The agreement here is excellent.

Figs (4) and (5) show comparisons of ROSPEC and NE213 (both uncorrected and corrected) free-field neutron energy spectra at 170 m. The same trends are observed. Table (1) gives fluence and kerma from both detectors over various energy intervals. Finally fig (6) compares the ROSPEC spectra at 170 m and 400 m. The expected structural enhancement at 400 m is readily apparent.

The BGO-measured gamma-ray energy spectra at 170 m and 400 m are shown in fig (7). Kerma values appear in table (1). All of the peaks, save the 511 keV peak from positron annihilation and the 2.2 MeV line from neutron capture in hydrogen can be attributed to prompt gamma-ray emission following neutron capture in nitrogen. Fig (8) shows the expected relative intensities (17) superimposed on the 400 m spectra - where, of course, the peaks are more well-defined than for the 170 m case. Fig (9) shows a comparison of the 400 m BGO spectra with the theoretical calculations (5). The agreement here is again excellent.

2.2.2 <u>In-Box Spectroscopy</u>

The neutron spectroscopy results for the ROSPEC and NE213/$BF_3$ systems inside the test bed (box) are shown in figs (10) and (11) for the uncorrected and corrected NE213 spectra respectively. Table (1) lists the associated kermas. The folly of using an NE213 system in a softer neutron environment is readily apparent. Figure (12) overlays the measured neutron spectra from ROSPEC both free-field and in the box.

It is very interesting to note that the free-field spectrum is almost exclusively softened with little absorption. This is readily apparent from the ROSPEC fluence comparison in table (1). Table (2) parameterizes the ROSPEC results.

Fig (13) overlays the free-field and in-box BGO gamma-ray energy spectra. Note that the external structure (due primary to neutron capture in nitrogen) is largely wiped out inside the vehicle. However peaks at 5.9, 7.6 and 9.3 MeV (due to thermal neutron capture in iron) and at 850 keV (due to inelastic scattering in iron) manifest themselves.

Table (1)

Spectroscopic Results

(i) Neutrons

| Location | Detector | Total Fluence ($n/cm^2$ - kWh) | Kerma (⟨600 keV) (mrad/kWh) | Kerma (⟩600 keV) (mrad/kWh) |
|---|---|---|---|---|
| 400 m FF | ROSPEC[a] | $2.34 \times 10^6$ | 1.41 | 2.55 |
| | NE213[b] (uncorrected) | $1.06 \times 10^6$ | 1.29 | 2.57 |
| | NE213 (corrected) | $2.27 \times 10^6$ | 1.55 | 2.63 |
| 400 m Box | ROSPEC | $1.88 \times 10^6$ | 1.44 | 1.23 |
| | NE213 (uncorrected) | $8.11 \times 10^5$ | 0.77 | 0.93 |
| | NE213 (corrected) | $1.26 \times 10^6$ | 1.44 | 1.43 |
| 170 m FF | ROSPEC | $4.58 \times 10^7$ | 25.9 | 54.9 |
| | NE213 (uncorrected) | $1.99 \times 10^7$ | 23.4 | 55.5 |
| | NE213 (corrected) | $4.50 \times 10^7$ | 33.9 | 60.0 |

(a) ROSPEC covers range 0.06 MeV - 4.5 MeV
(b) NE213/$BF_3$ system covers entire range thermal -12 MeV

(ii) Gamma-Ray

| Location | Kerma (mRad/kWh) |
|---|---|
| 400 m FF | 1.56 |
| 400 m Box | 0.38 |
| 400 m WOODS | 1.35 |
| 170 m FF | 22.6 |

Table (2)

Parametric Values From ROSPEC Neutron Spectroscopy

| Location | Parameter | |
|---|---|---|
| | Mean Energy (MeV) | Mean Kerma (Rad $cm^2$) |
| 400 m FF | 0.766 | $1.71 \times 10^{-9}$ |
| 400 m Box | 0.497 | $1.41 \times 10^{-9}$ |
| 170 m FF | 0.826 | $1.65 \times 10^{-9}$ |

(Note FF = Free Field)

The primary purpose of the test bed is to provide a simplistic vehicle for experimental and theoretical comparison of radiation transmission. A direct comparison may be made here of the two relevant parameters which may be experimentally obtained-neutron and gamma-ray reduction factors, (NRF and GRF) defined as:

$$NRF = \frac{\text{neutron kerma outside box}}{\text{neutron kerma inside box}} \quad (1)$$

$$GRF = \frac{\text{gamma-ray kerma outside box}}{\text{gamma-ray kerma inside box}} \quad (2)$$

The measured values are presented in table (3) and (4) with comparisons to theoretical calculations (18,19). The calculations come directly from the NATO physical dosimetry subcommittee of RSG-5 computer intercomparison. Here the APG scenario was simulated (complete with test-bed).

The theoretical calculations overestimate the experimentally measured NRF by 6% and underestimate the experimentally measured GRF by 14%. To be fair, the calculations employed on old source term, and did not match the exact soil and atmospheric conditions at the time of the experiments - which could account for some of the discrepancies. More work appears to be needed.

**Table (3)**

**Comparison of Measured and Calculated Neutron and Gamma-Ray Reduction Factors for Test Bed Configuration**

(a) Neutrons

| Method | NRF |
|---|---|
| ROSPEC | 1.48 |
| Calculations (Average of Refs (18) and (19)) | 1.59 ± .01 |

(b) Gamma Rays

| Method | GRF |
|---|---|
| BGO | 4.10 |
| Calculations (Average of Refs (18) and (19)) | 3.52 ± .13 |

Another aspect of the box (and future actual vehicle) measurements is their relation to Transient Radiation Effects on Electronics (TREE) work. Neutron damage to electronics is most often defined in terms of 1 MeV equivalent Si fluence, defined as

$$\phi_{eq}(1\text{MeV}) = \frac{\int_{E_{min}}^{E_{max}} \phi(E)\, K_D(E)\, dE}{K_D\ (1\ \text{MeV})} \qquad (3)$$

where

$\phi(E)$ = incident neutron energy-fluence spectrum
$K_D(E)$ = neutron kerma-displacement factor for Si
$E_{min}$, $E_{max}$ = limits of spectral measurement

Various NATO documents (20) have suggested that the 1 MeV equivalent reduction factor can be approximated by NRF. In experiments, many reduction factors may be measured including total fluence reduction factor (i.e. from ROSPEC) or NE213 fluence ()600 keV) reduction factor. Table (4) lists the measured values of the various reduction factors. Clearly the NRF does give the best approximation to the 1 MeV equivalent reduction factor. This may have been expected from an examination of fig (14). Here the tissue and Si displacement kermas have been overlayed for comparison purposes only. Note that for low (fission) energies the general shape of the curves is similar enough that the ratio of the two is in reasonable agreement. Note, however, that for spectra which contain a sizeable higher energy (fusion) component the

agreement may be expected to be somewhat less. This will be the subject of future DREO work.

**Table (4)**

**Various Neutron Reduction Factors for Test Bed Configuration**

| System | | Value |
|---|---|---|
| ROSPEC-Measured | NRF | 1.48 |
| ROSPEC + NE-213 | NRF | 1.56 |
| 1 MeV Equivalent | NRF | 1.43 |
| Fluence (ROSPEC) | NRF | 1.16 |
| NE213 ()600 keV) Fluence | NRF | 1.72 |
| BD-100R | NRF | 1.41 |

2.2.3 In-Woods Spectroscopy

Owing to technical difficulties with the NE213/$BF_3$ system the neutron spectrum in the woods (approximately 80' in from the clearing at 400 m) could not successfully be unfolded. However the BGO gamma-ray spectrum was acquired and is plotted together with the free-field 400 m spectrum in fig (15). Note that the same peaks are present in each spectrum, but that they are more enhanced for the in-woods case, especially the 2.2 MeV hydrogen capture line. Apparently the woods offer shielding from the direct gamma-ray continuum, while neutron capture within the forest enhance the discrete components.

While there was no neutron spectrum available, the BD 100R was deployed both free-field, and in the woods. The results were then analyzed in terms of kerma, and the NRF and GRF afforded by the woods appear in table (5).

**Table (5)**

**Measured In-Woods Reduction Factors**

| Factor | Detector | Value |
|---|---|---|
| NRF | BD-100R | 2.98 |
| GRF | BGO | 1.16 |

2.2.4 Comparison of Spectra to Previous Work

Finally, this spectroscopic review would not be complete without mention of an extremely interesting observation. Fig (16) shows a comparison of the 1989 ROSPEC-measured spectrum to a measurement made at the same location in 1987 (21). Clearly there is a large change in the neutron spectrum, especially at lower energies. Again suspect causes are air and soil moisture

content. Fig (17) shows the comparison for the NE213 data in 1989 and 1987. The only discrepancy would be that the 1989 results are lower from 2-4 MeV. If the large variation in neutron energy spectra is real, this could account for many of the discrepancies previously reported. A ROSPEC-type system is necessary to perform neutron spectroscopy under a variety of environmental conditions to examine the extent of these effects.

2.2.5 BD-100R Dosimetry

The BD-100R was deployed at the free-field (400 m and 170 m), in-box and, as previously mentioned in-woods locations. The BD-100R detectors are calibrated to read in bubbles/mrem (PuBe) and must be corrected for temperature sensitivity (5). This procedure is extremely straightforward (and is one of the more attractive features of the use of the bubble detector) and allows quick and accurate determination of the neutron dose equivalent, as recorded column 2 of table (6).

The conversion from dose-equivalent to kerma is, of course, never trivial. it has been suggested that a Q-factor of 12.44 be used for a degraded fission spectrum (25), where the Q-factor may be defined as:

$$Q = \frac{\int DE(E)\ \phi(E)\ dE}{\int K(E)\ \phi(E)\ dE} \qquad (4)$$

where DE(E) = dose equivalent/energy response

$\phi(E)$ = neutron fluence

K(E) = kerma/energy response

Table (6) BD-100R Results

| Dosimeter Location | Dose Equivalent (mrem/kWh) | Kerma Using Q = 12.44 (mRad/kWh) | ROSPEC Q Value (rem/Rad) | Kerma Using ROSPEC (mRad/kWh) | ROSPEC Measured KERMA (mRad/kWh) |
|---|---|---|---|---|---|
| FF (400 m) | 44.35 | 3.57 | 11.44 | 3.88 | 3.96 |
| In Box (400 m) | 31.51 | 2.53 | 11.26 | 2.80 | 2.67 |
| In Woods (400 m) | 14.89 | 1.20 | - | - | |
| FF (170 m) | 976.8 | 78.5 | 11.59 | 84.28 | 80.8 |

Using this value, the kerma values appearing in column 3 of table (6) are derived.

A more accurate method to determine neutron kerma from the BD 100-R results is to make use of the experimentally determined neutron fluence from ROSPEC as an input as $\phi(E)$ in eq'n (4). Using this, the values of Q appearing in column 4 of table 6 are determined, leading to the kermas in column 5 of table (6). Finally column 6 of table 6 lists, again, the ROSPEC-determined kerma. Note that the BD-100R has a lower threshold of about 100 keV, while ROSPEC has upper threshold around 4.5 MeV. The fact that the percentage of kerma below 100 keV is roughly equal to that above 4.5 MeV makes a direct comparison of the BD-100R to ROSPEC meaningful.

Using an experimentally determined value of Q does yield more consistent ($\langle$5%) results. However even using the approximation gives results good to within ~12%. The above should prove categorically that in fision or degraded fission environments the bubble dosimeter (BD-100R) is applicable as an absolute dosimeter. Its use in mixed (fission/fusion) environments will be examined more closely in a upcoming DREO report.

2.2.6 In-Phantom In-Vehicle Neutron Dosimetry

The relationship between the measured response of a dosimeter, as worn at a particular location on the body, to such parameters as free-field kerma has been measured, calculated and favourably compared for the case of an anthropomorphic phantom at the NATO standard test point (5). The results of different calculations, for actual weapons scenarios (22), have been used to derive general relationships between dosimeter readings and free-field kerma for inclusion in NATO documents (23). However for the case of the man-in-vehicle the relationships may not be that similar, due primarily to differences in the angular distributions of the incident radiation. Indeed, this problem has led to a call within NATO for a definition of an "effective protection factor" (24) to make dosimeter readings more meaningful.

As a preliminary investigation of these effects DREO deployed its RT-200 anthropomorphic phantom (5) inside the test bed. The phantom was outfitted with dosimeters at the left chest, front belt, left wrist, right wrist, lower back and mid-gut locations and oriented facing, right hand side to and back to the core (as in (5)). A comparison of the free-field and in-box results in terms of neutron transmission factors appears in table (7) (NTF = dosimeter bubbles at phantom location/FF bubbles).

Table (7)

Neutron Transmission Factors for Free-Field and In-Box Cases

NTF

| | Phantom Orientation w.r.t. Core | | | | | |
|---|---|---|---|---|---|---|
| | Facing | | RHS To | | Back To | |
| | FF | In Box | FF | In Box | FF | In Box |
| Dosimeter Location | | | | | | |
| Left Chest | 0.97 | 0.99 | 0.74 | 0.70 | 0.75 | 0.68 |
| Belt (Front) | 0.84 | 0.97 | 0.75 | 0.73 | 0.50 | 0.49 |
| R. Wrist | 0.68 | 0.84 | 0.83 | 0.90 | 0.88 | 1.06 |
| L. Wrist | 0.75 | 0.96 | 0.59 | 0.57 | 0.89 | 1.04 |
| Lower Back | 0.41 | 0.54 | 0.79 | 0.42 | 0.99 | 0.84 |
| Mid Gut | 0.34 | 0.09 | 0.21 | 0.07 | 0.18 | 0.07 |

The general trend of these results would seem to be that the value of neutron transmission factor on the phantom is not altered much by the addition of the test-bed. The values are generally within experimental errors of each other, especially when one realizes that the exotic temperature monitoring device used in (5) was absent here. Only the dosimeter reading 'lower back - phantom right hand side to' would appear to be grossly in error - i.e. greater than the 'lower back - phantom facing core' value. This may be due in part to the difficulty of orientation positioning, especially when the complex shape around the lower back dosimeter is considered. Clearly more experimental work is needed.

The most interesting case is that of the mid-gut dosimeter. The values from the two scenarios differ radically. It is interesting to note that the mid-gut location was the one in which the DREO measured results at the test point differed most from the calculations of Kaul (5). As means from the three orientations we have:

| | |
|---|---|
| NATO Standard Test Point (Miniature BD-100R) | $0.24 \pm 0.09$ |
| NATO Standard Test Point (Calculations) | $0.12 \pm 0.03$ |
| NATO Test-Bed (BD-100R) | $0.08 \pm 0.01$ |

Note that the spread has been reduced significantly for the test-bed case. This is due to the use of more (3 vs 1) dosimeters, of greater sensitivity and more well-defined energy response. (Indeed 'miniature' BD-100 s were used in 1987). The greater agreement with the calculations may be fortuitous (although the results at other positions suggest otherwise) and awaits corrobation from detailed theoretical work.

Finally a word on the use of gamma-ray dsoimeters inside the test bed. The free-field kerma of 0.38 mRad/kWh may be expected to be only increased or decreased slightly by the addition of the phantom. The most sensitive gamma-ray dosimeters applicable to phantom work (TLD 400s) require ~ 20 mRad. Thus around 50 kWh - or 8 hours at full facility power is required for meaningful results. The situation becomes even more untenable for more heavily shielded configurations.

## 3. Conclusions and Recommendations

As a result of this APG work, a great deal of controversy and ambiguity concerning experimental data at the 400 m NATO standard test point has been overcome. Using this work as a basis, future plans to better characterize the radiation environment - both its measurement and calculation- have emerged. The following list of recommendations is intended as a guideline as to focal points for the future work.

1) A ROSPEC - based system should be accepted as the (current) standard for all NATO neutron spectroscopy in fission/degraded fission environments. In such spectra, the system may act as a stand-alone unit. For spectra with a significant higher energy (fusion) component, an NE213 or He-4 system must augment ROSPEC.

The ROSPEC-based system must be used by APG staff to perform a complete analysis of the influence of ground/air moisture (or any other effects) on the neutron spectrum at the NATO standard reference point.

The BGO spectrometer should be the standard for all NATO gamma-ray spectroscopy.

2) The BD 100R should be the NATO standard neutron dosimeter. Its efficacy as an absolute dosimeter in the fields examined here has been verified.

3) For now, TLD 400s should be recognized as the NATO standard gamma-ray dosimeter (again in the absolute sense). However the TLD 400 is incompatible (too insensitive for simultaneous work) with the BD 100R for many shielding experiments. Thus a new, more sensitive device should be sought. Either physically larger TLDs or a gamma-ray sensitive bubble detector appear to be the main options.

4) The BDS spectrometer set is the fastest way of achieving crude (6 group) neutron spectral data. It is also the only way of getting any spectral information in small, confined areas such as in-vehicle or in-phantom.

5) A version of the RT-200 phantom with articulating limbs should be designed, built and standardized for NATO work. New work at Radiology Support Devices on (more tissue equivalent) polyester fabrics may be helpful here.

6) More work on arboreal shielding, both theoretical and experimental, needs to be done, as these scenarios are more realistic.

7) Future work on the test-bed should include:

- non-uniform shielding
- various liner materials
- internal structure
- more than one phantom inside.

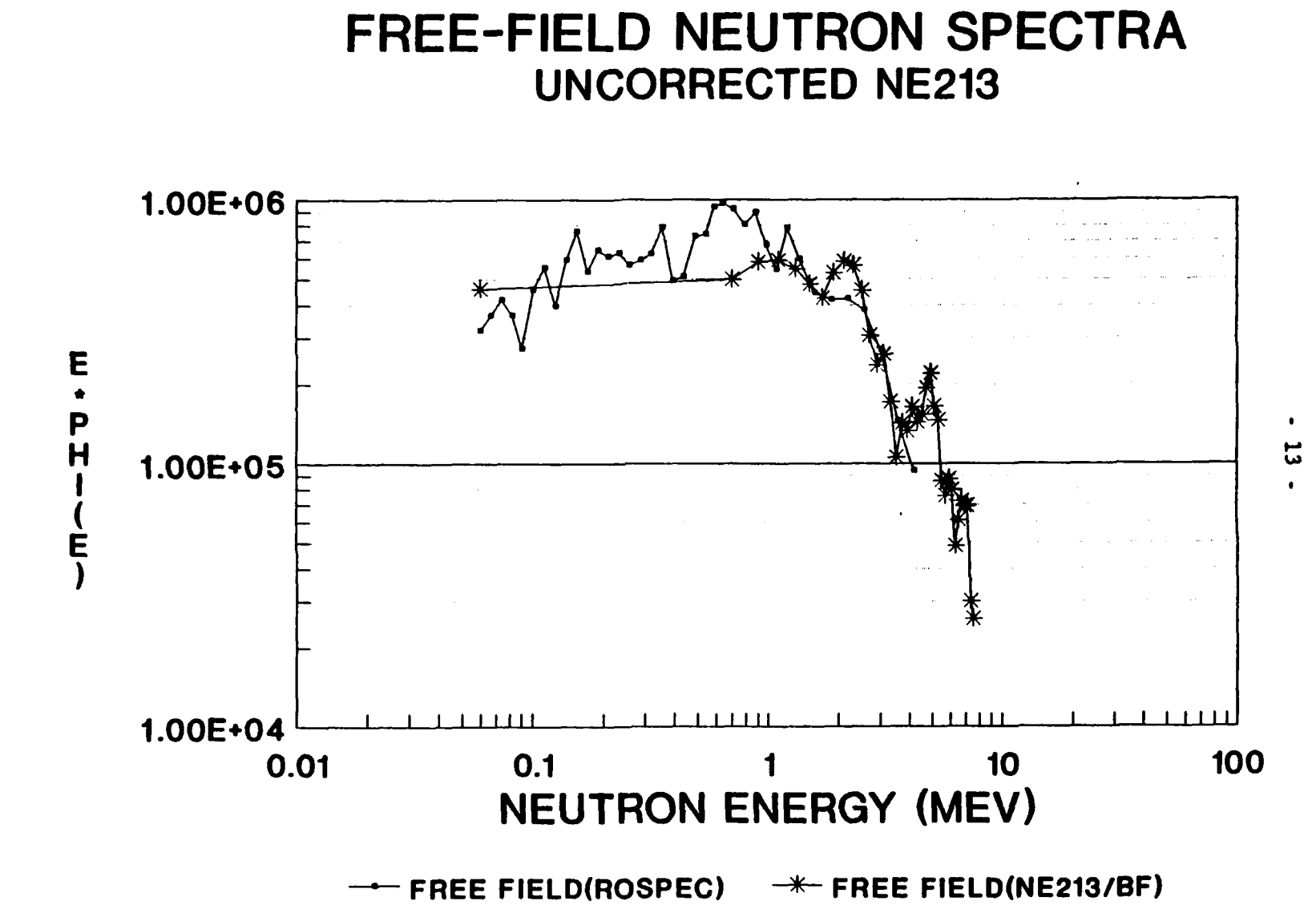


Figure 1: Comparison of neutron energy spectra at the NATO standard reference point as measured by ROSPEC and the NE213/$BF_3$ systems. Note that below ~ 1 MeV, the NE213/$BF_3$ system considerably underestimates the fluence.

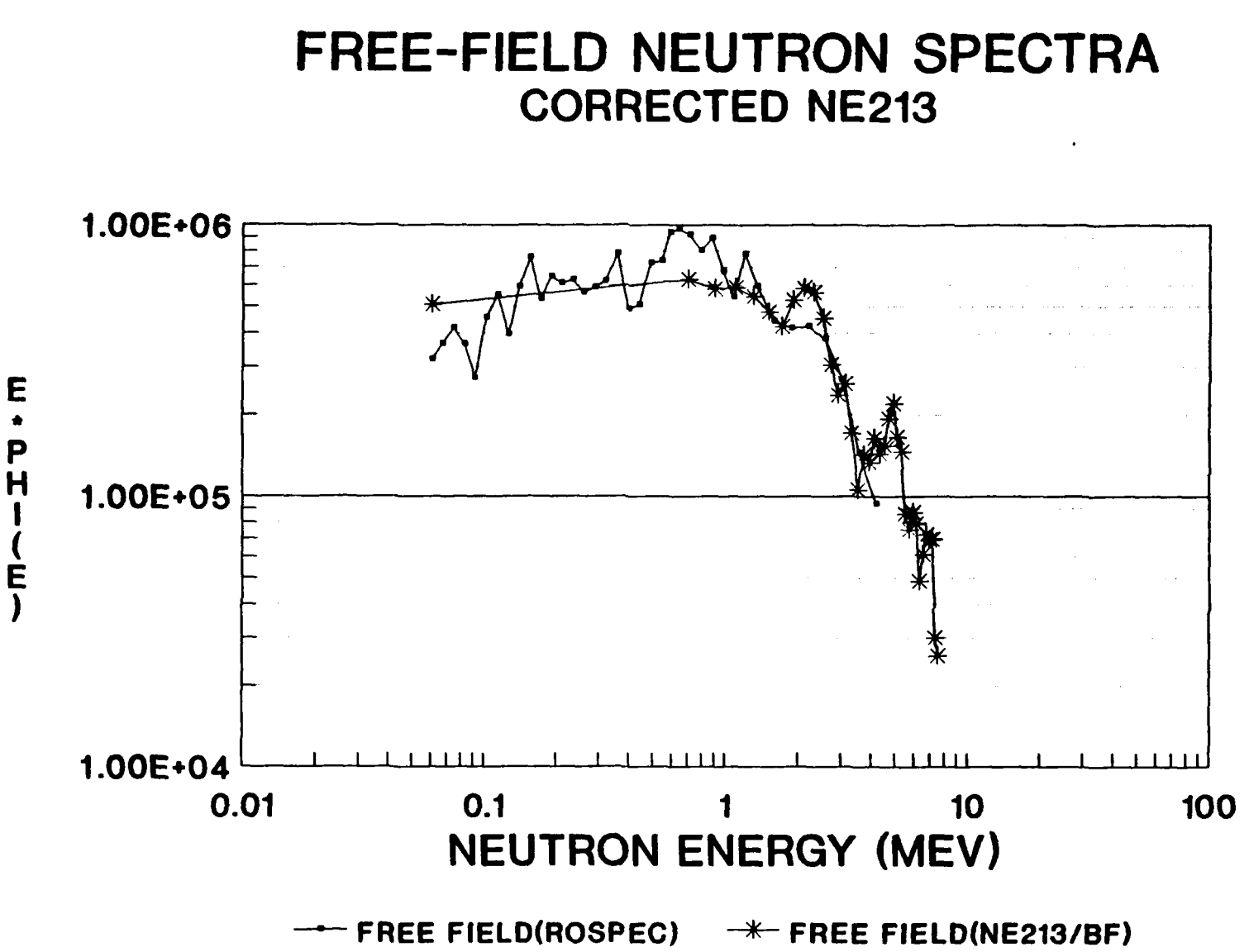


Figure 2: Comparison of neutron energy spectra at the NATO standard reference point as measured by ROSPEC and the NE213/$BF_3$ systems with the corrections to the latter as described in the text.

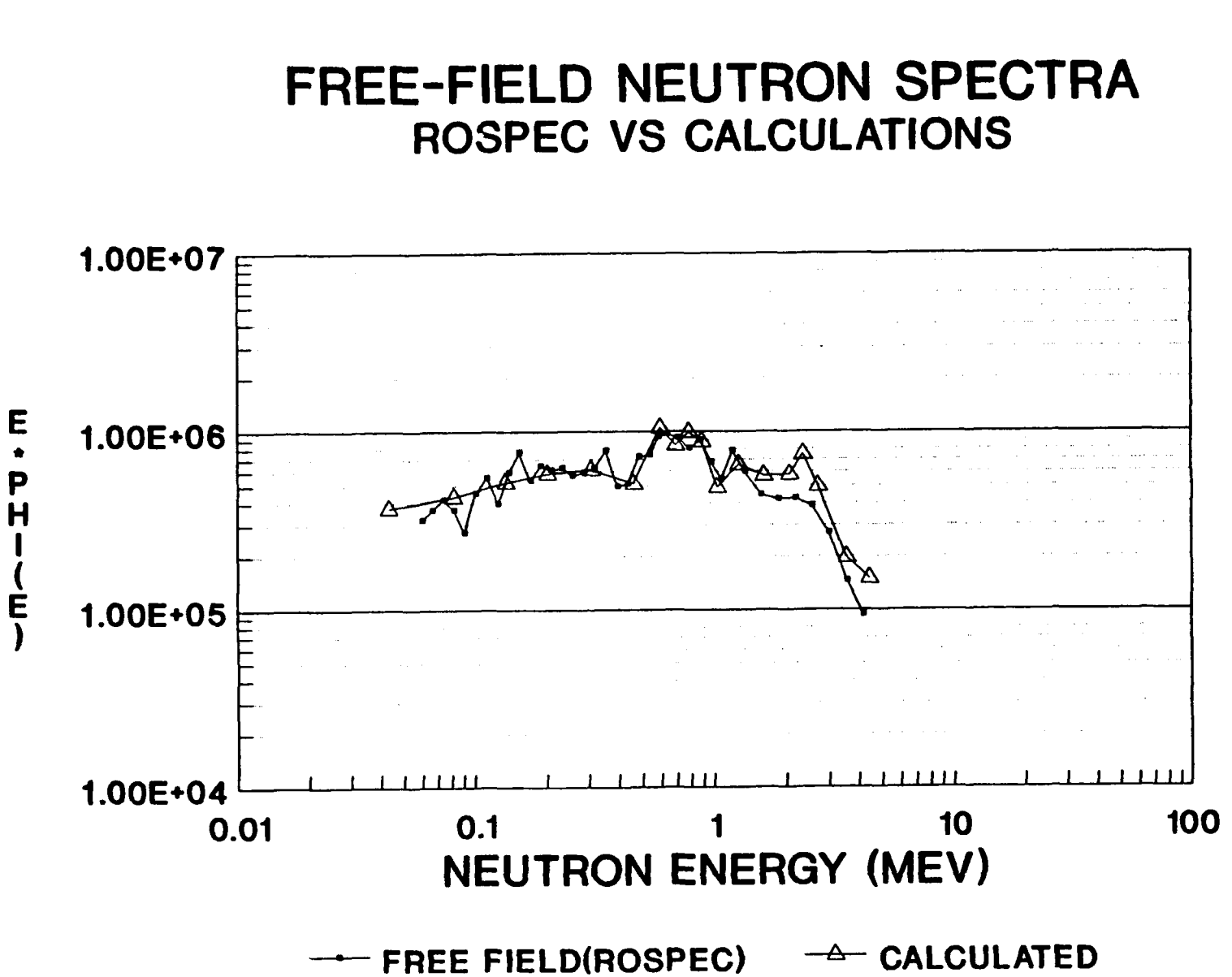


Figure 3 (a): Comparison of ROSPEC - measured and calculated neutron energy spectra at the NATO standard reference point over the energy range 60 keV - 4.5 MeV.

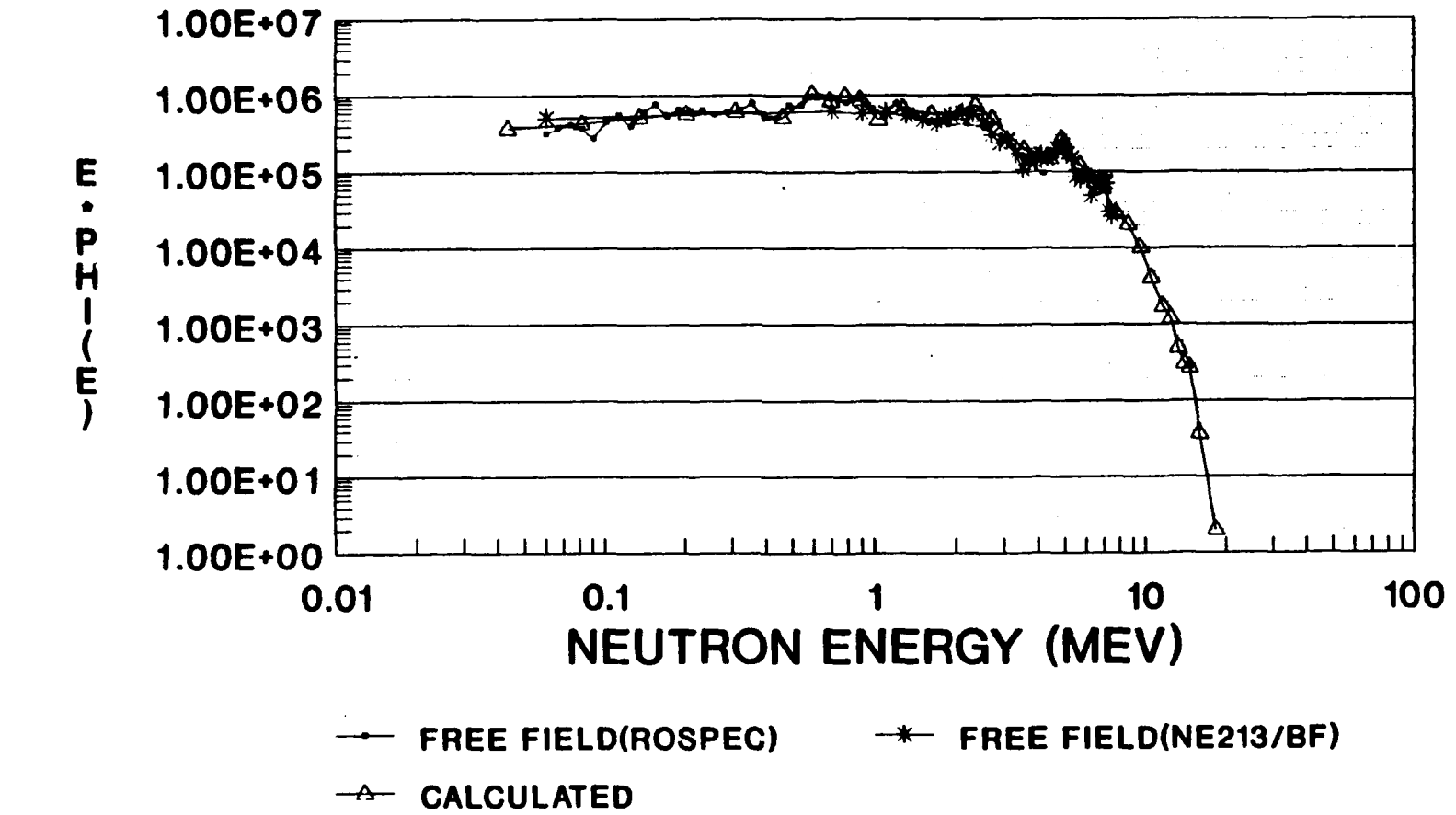


Figure 3 (b): Comparison of ROSPEC and NE213/$BF_3$ - measured with calculated neutron energy spectra at the NATO standard reference point over the energy range 60-keV - 7 MeV.

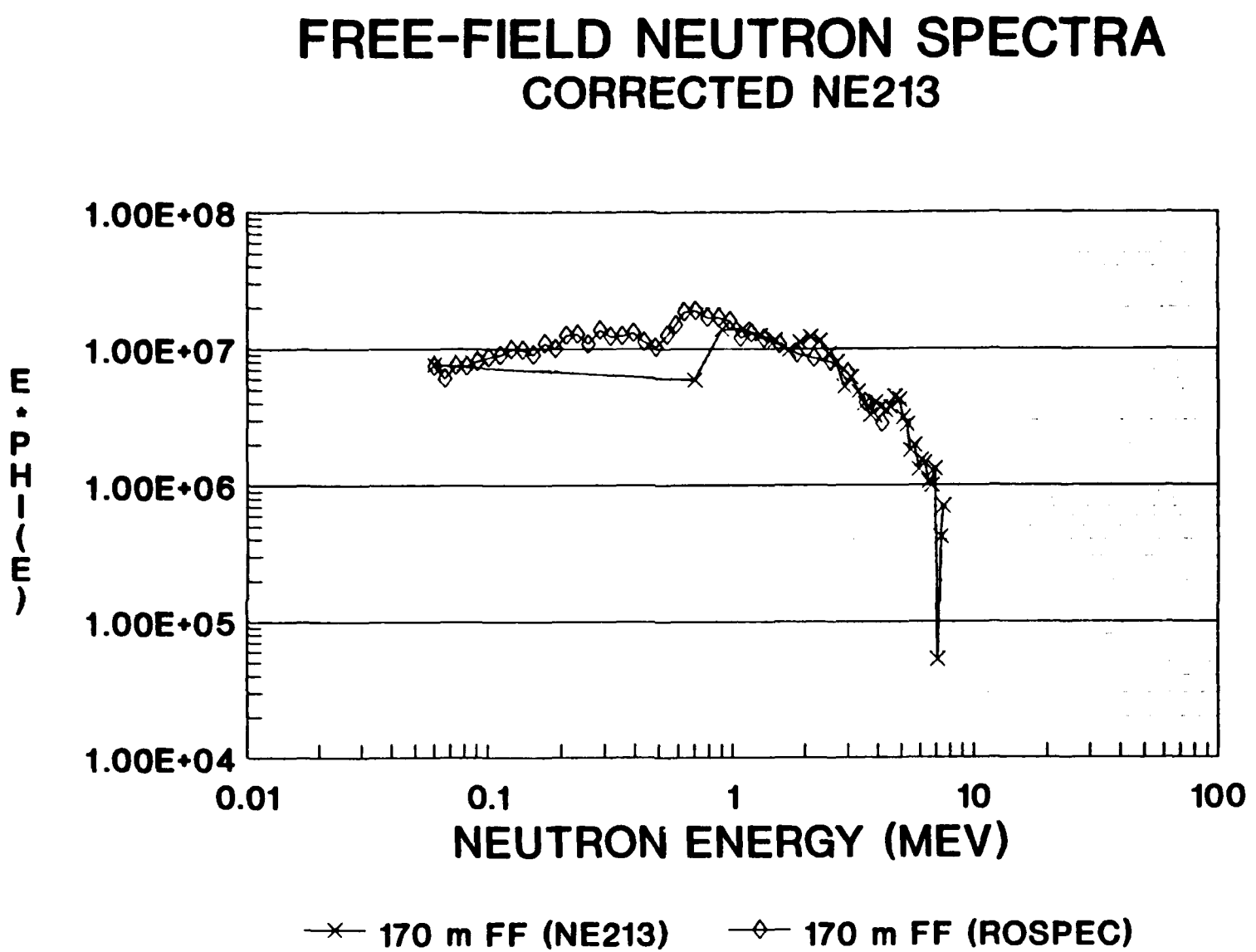


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Figure 4: Comparison of neutron energy spectra at 170 m from the core as measured by ROSPEC and the NE213/$BF_3$ systems (uncorrected).

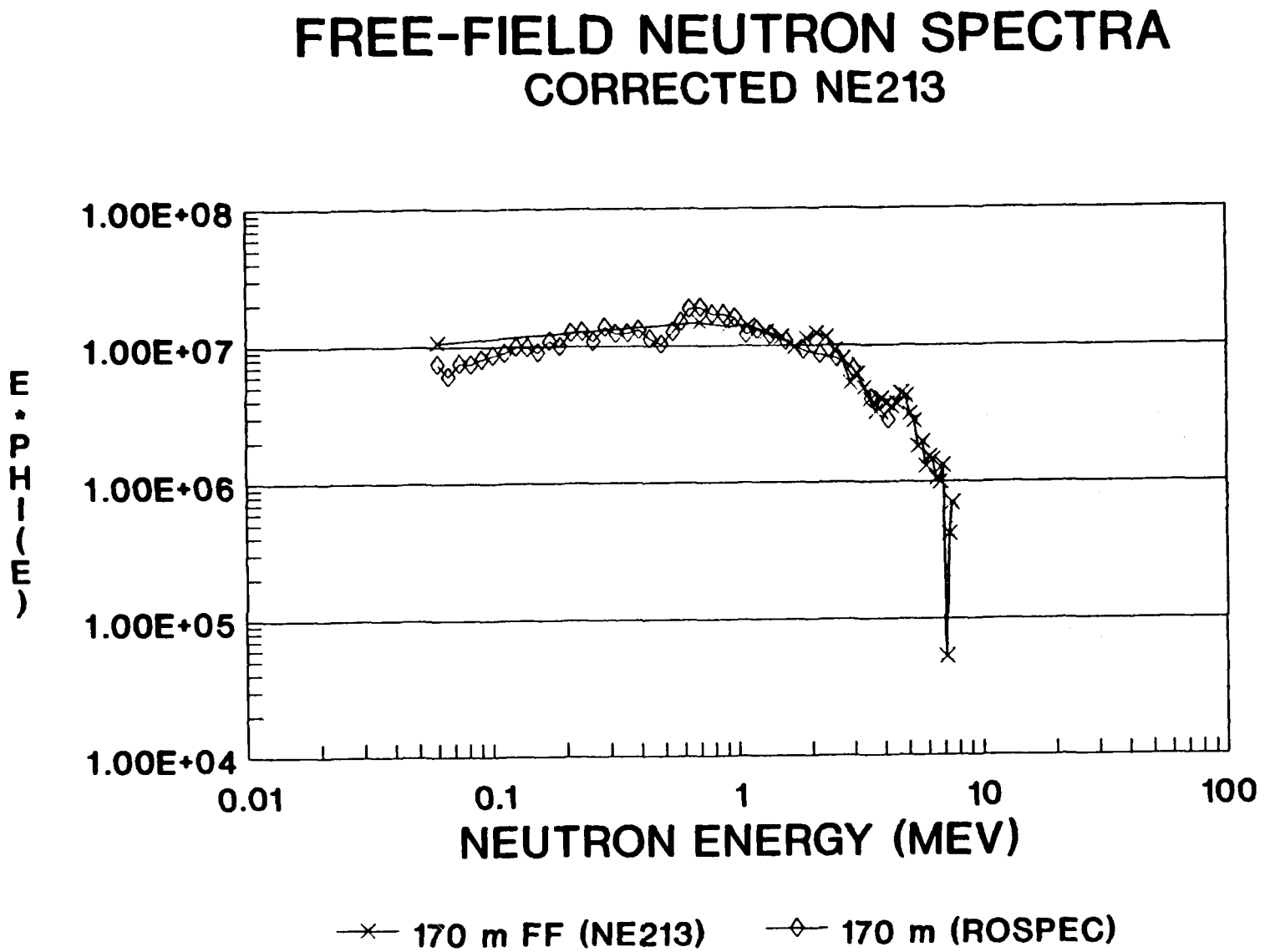



Figure 5: Comparison of neutron energy spectra at 170 m from the core as measured by ROSPEC and the NE213/$BF_3$ systems, applying the corrections as described in the text.

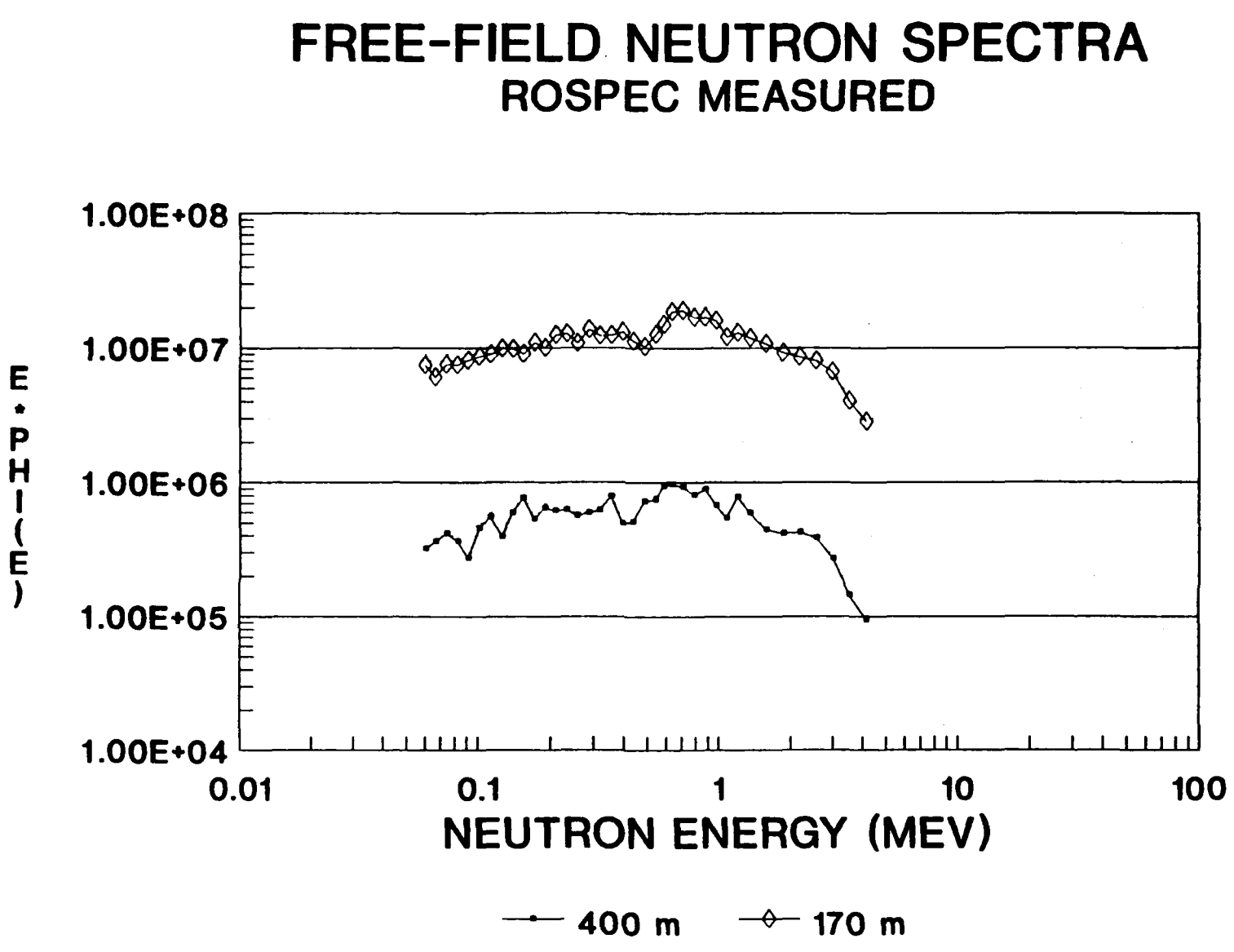



Figure 6: Comparison of the ROSPEC-measured neutron energy spectra at 170 m and 400 m from the core, showing the expected structural enhancement at 400 m.

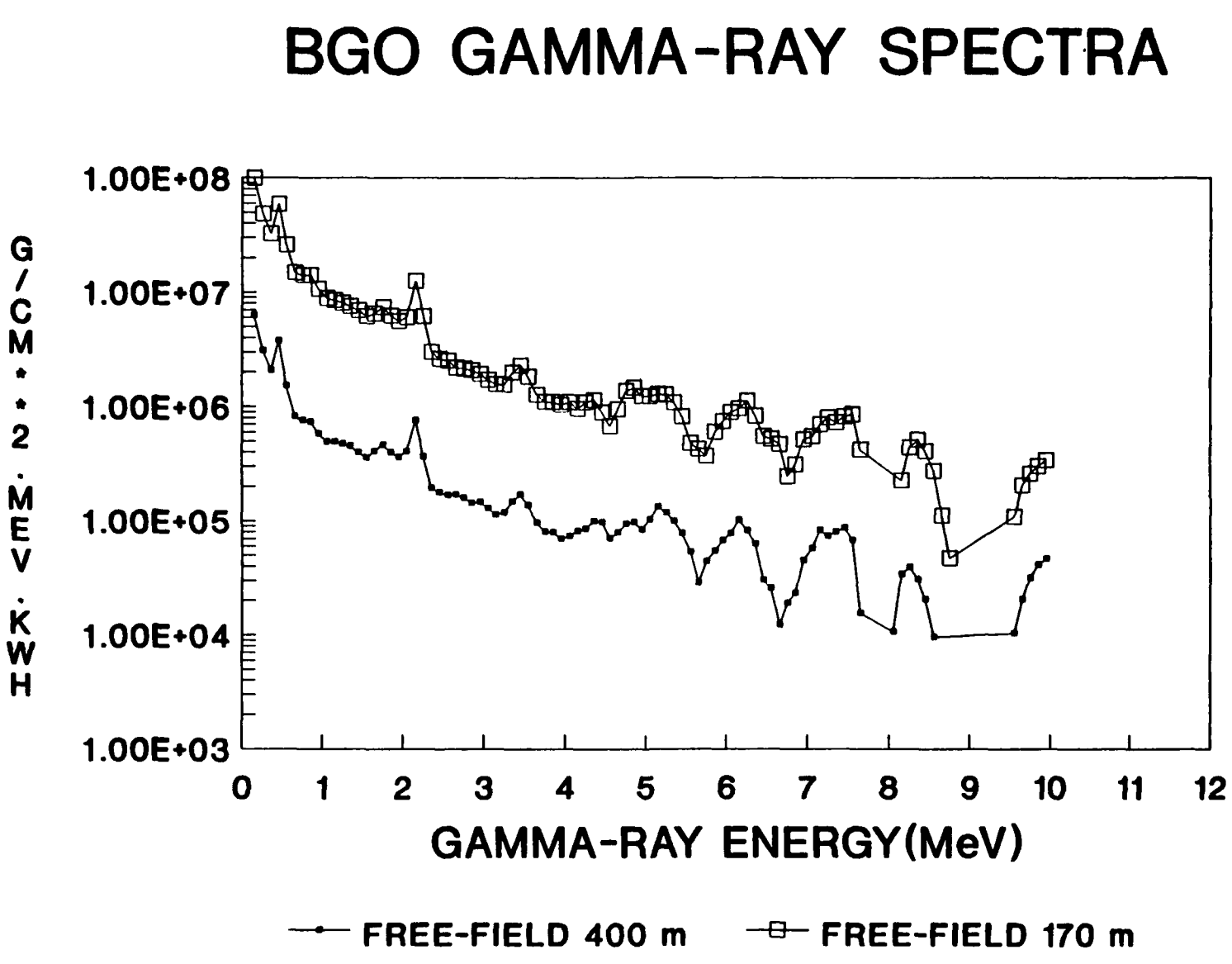



Figure 7: Comparison of BGO-measured gamma-ray energy spectra at 170 m and 400 m from the core. The effects of neutron-capture is more pronounced for the 400 m case, as expected.

# BGO GAMMA-RAY SPECTRA

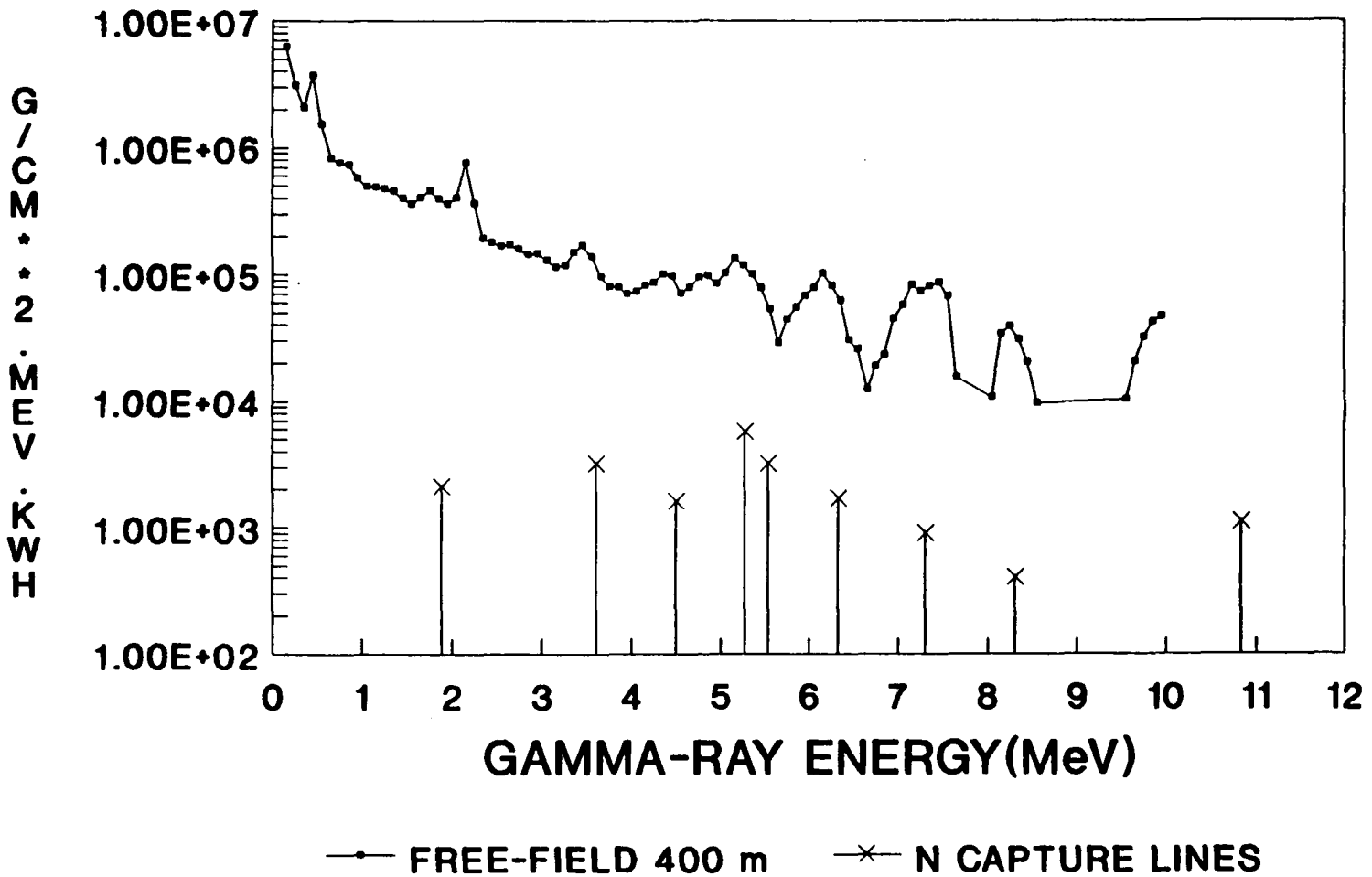



Figure 8: Overlay of BGO-measured gamma-ray energy spectrum at the NATO standard reference point and the neutron capture lines from nitrogen - clearly indicating the origin of the bulk of the structure.

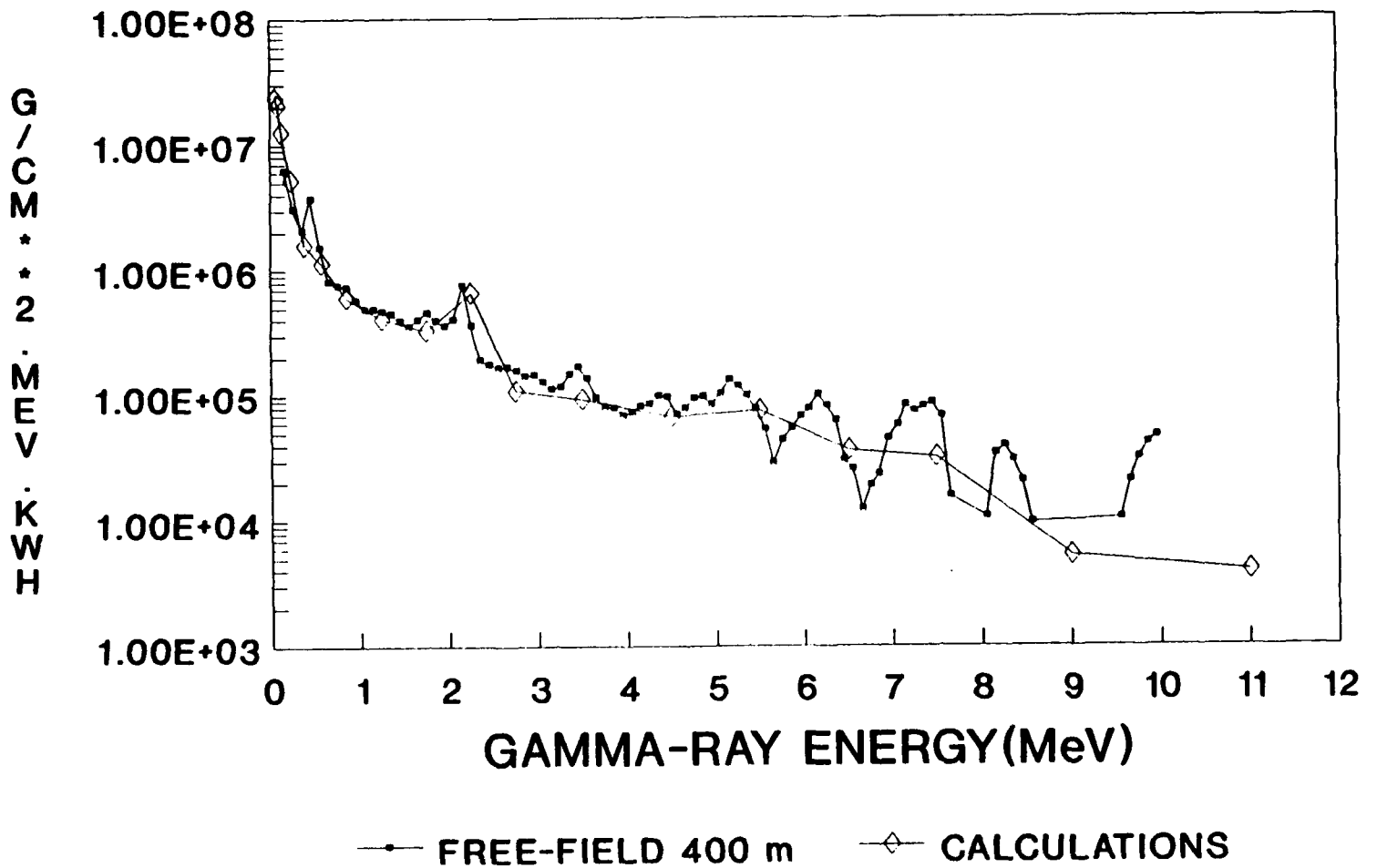
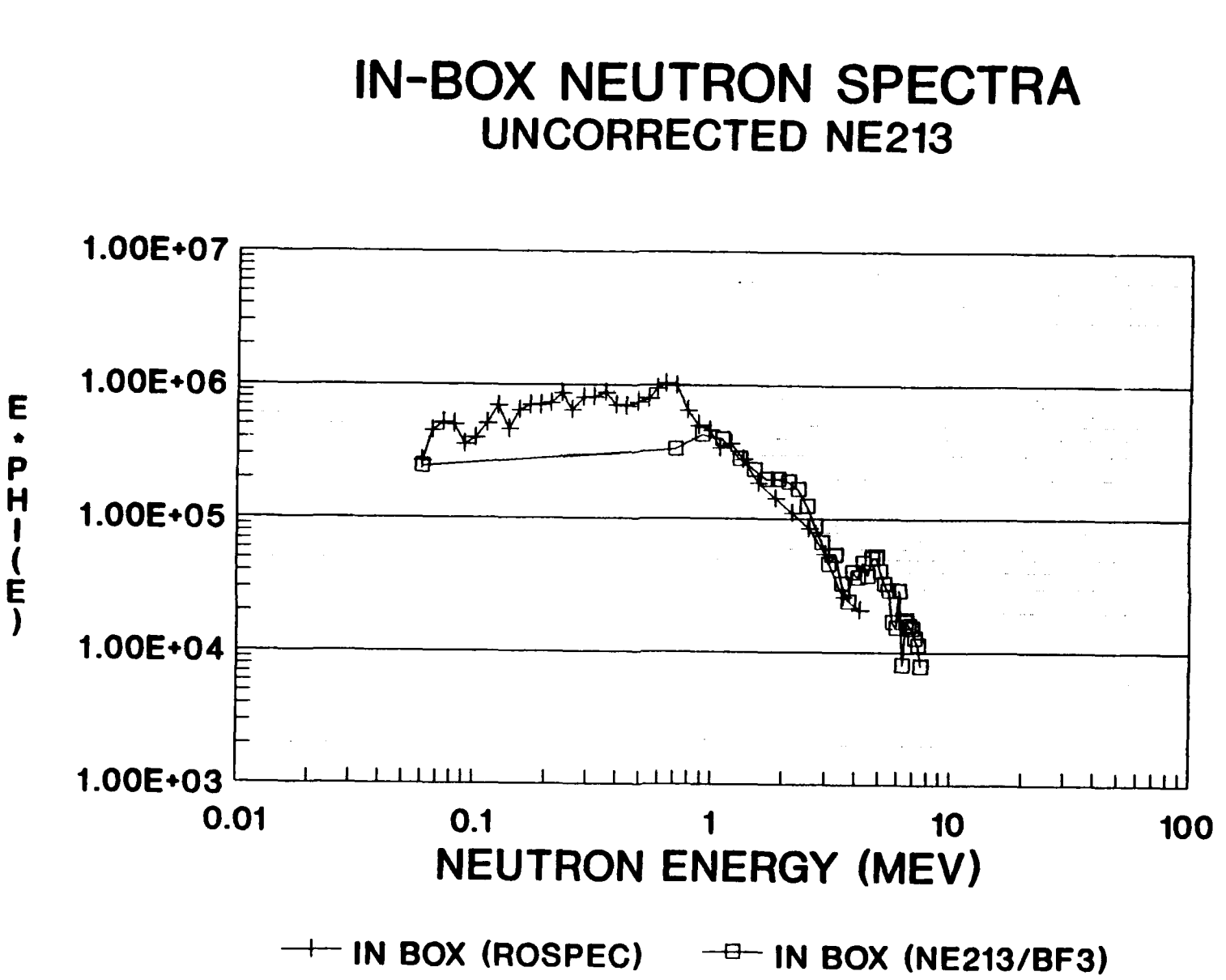



Figure 9: Comparison of BGO-measured and calculated gamma-ray energy spectra at the NATO standard reference point.




NORMALIZED PER KWH

Figure 10: Comparison of the neutron energy spectra in the test bed as measured by ROSPEC and the NE213/$BF_3$ systems (uncorrected).

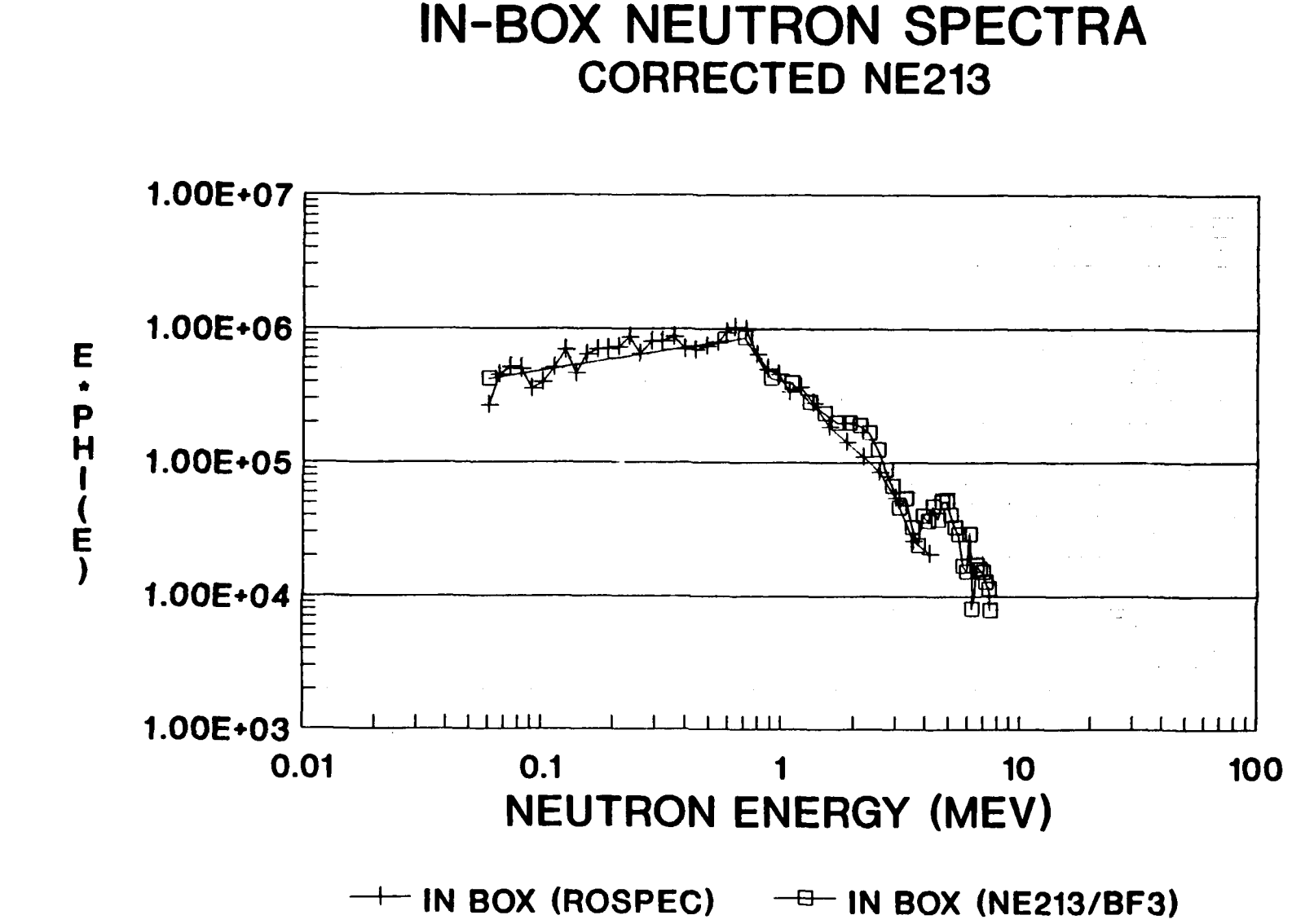



Figure 11: Comparison of the neutron energy spectra in the test bed as measured by ROSPEC and the NE213/$BF_3$ systems, applying the corrections as in the text.

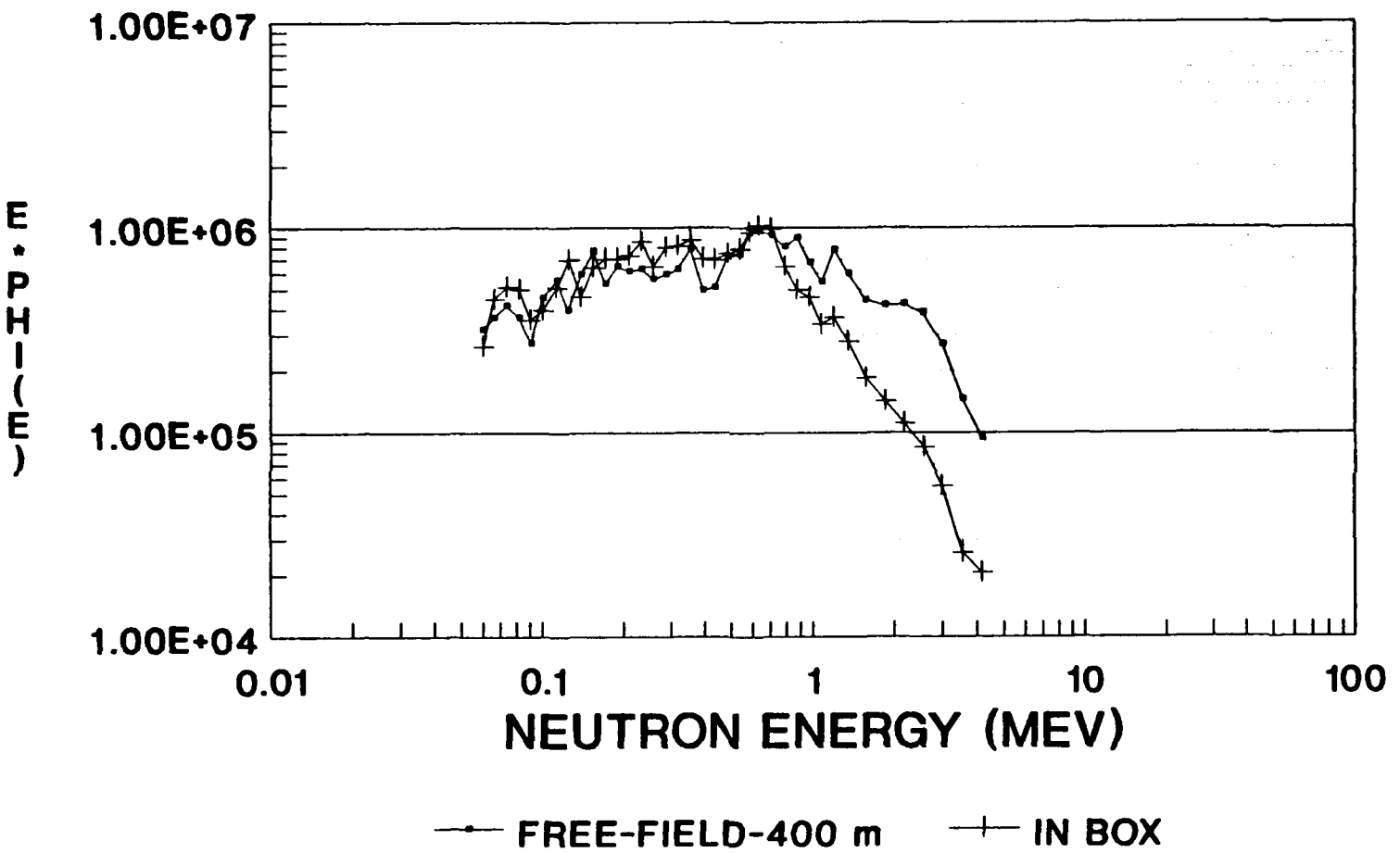



Figure 12: Comparison of the ROSPEC-measured neutron energy spectra both at the NATO standard reference point and in the test bed. Note the outside spectrum is almost exclusively softened.

# BGO GAMMA-RAY SPECTRA

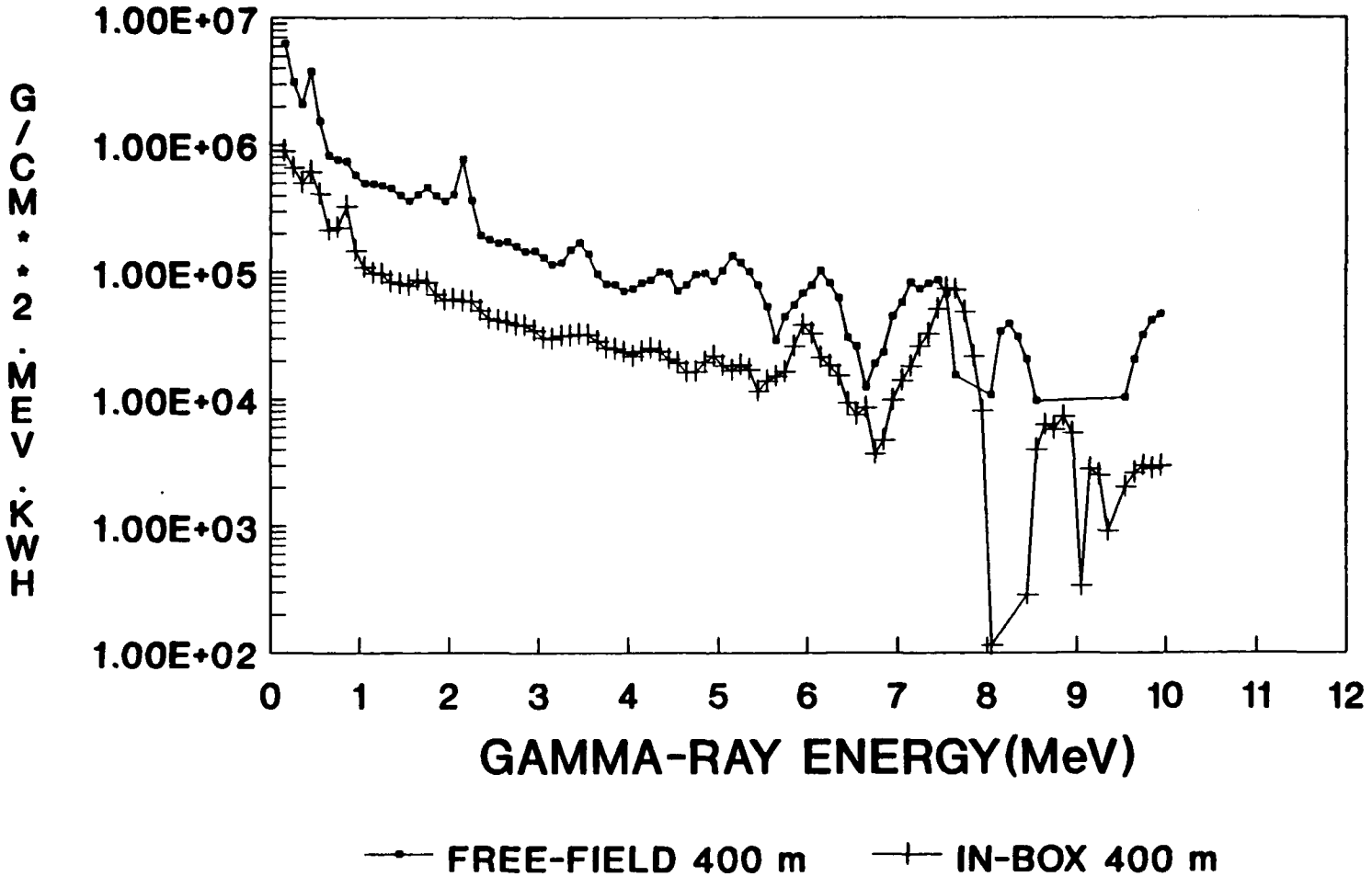



Figure 13: Comparison of the BGO-measured gamma-ray energy spectra both at the NATO standard reference point and in the test bed. Note the presence of neutron-capture gamma rays from iron occuring inside the box.

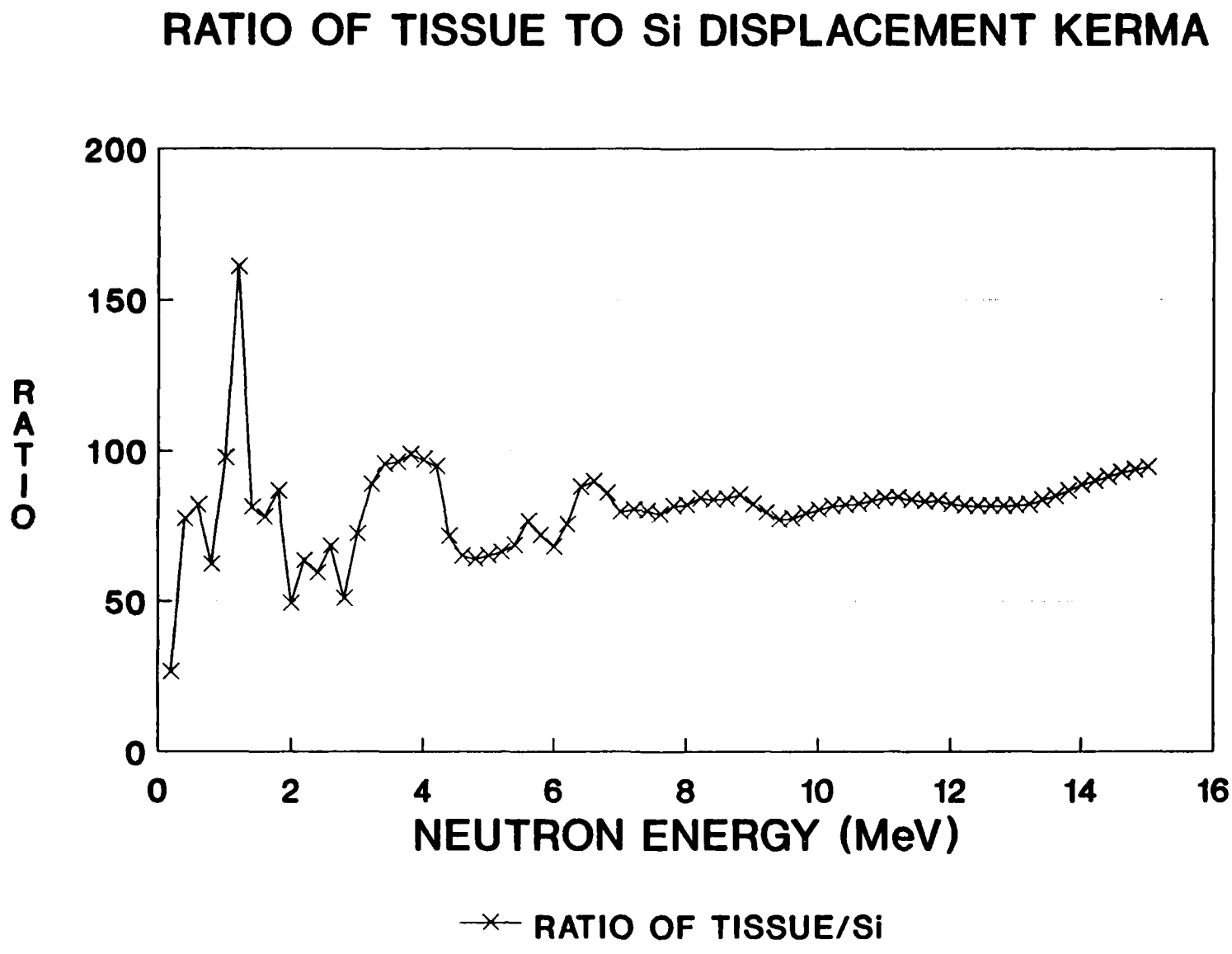



Figure 14: Overlay of neutron tissue kerma and silicon displacement kerma responses.

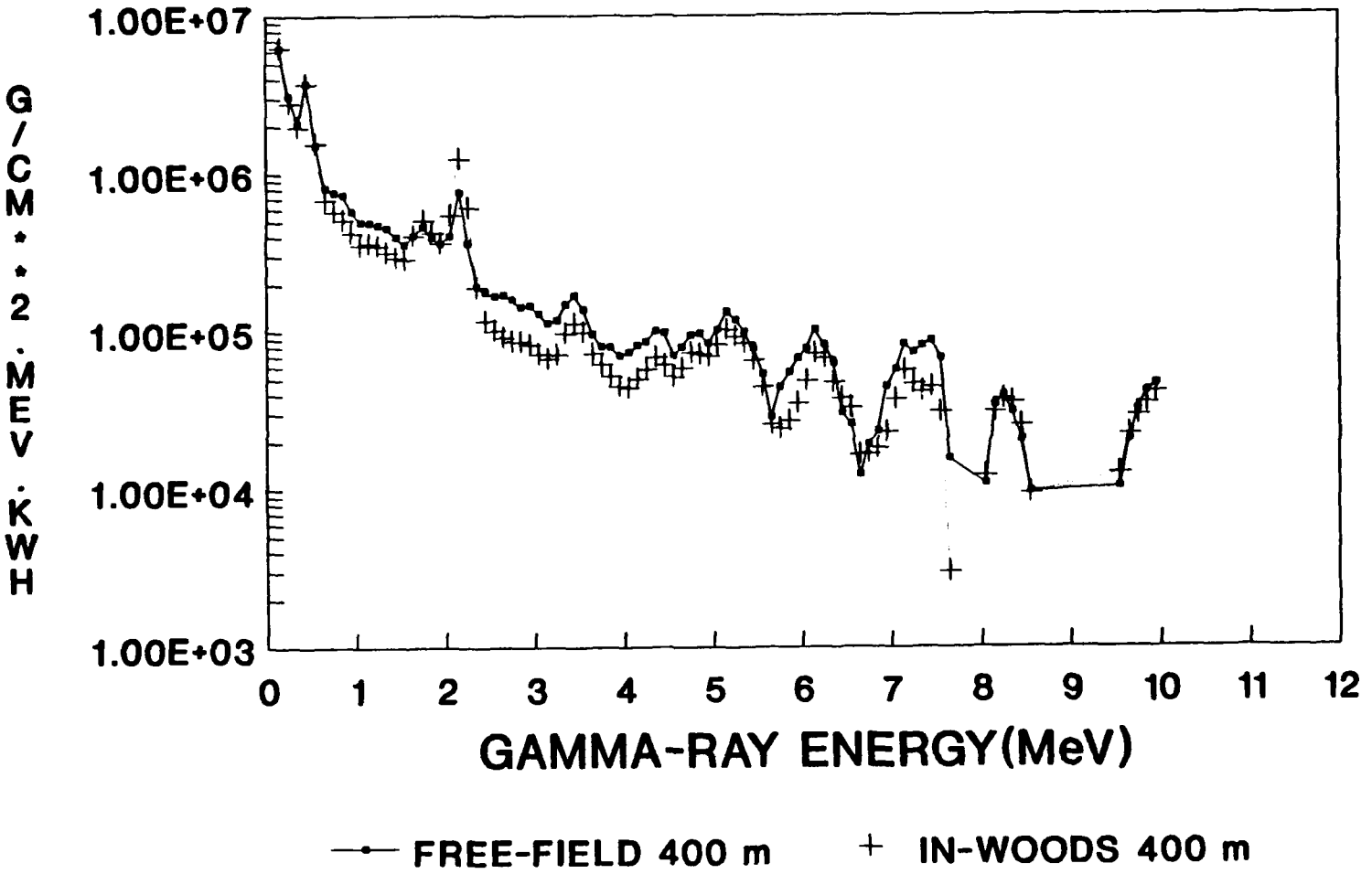



Figure 15: Comparison of the BGO-measured gamma-ray energy spectra at both the NATO standard reference point, and in the woods 400m from the core.

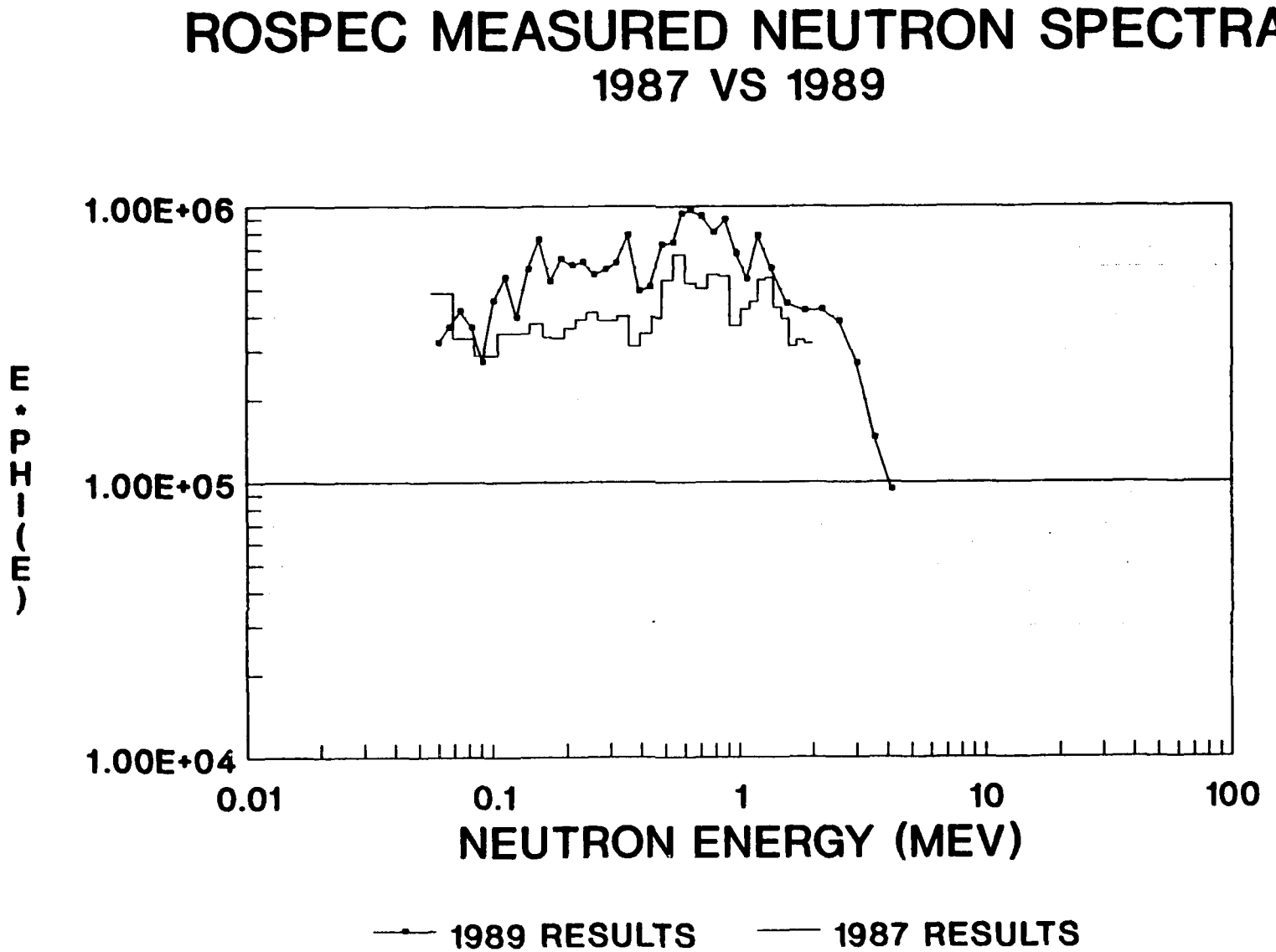



Figure 16: Comparison of ROSPEC-measured neutron energy spectra at the NATO standard reference point in 1987 and 1989. Note the large increase in the neutron fluence below 1 MeV for the 1989 case. The cause of this has yet to be determined.

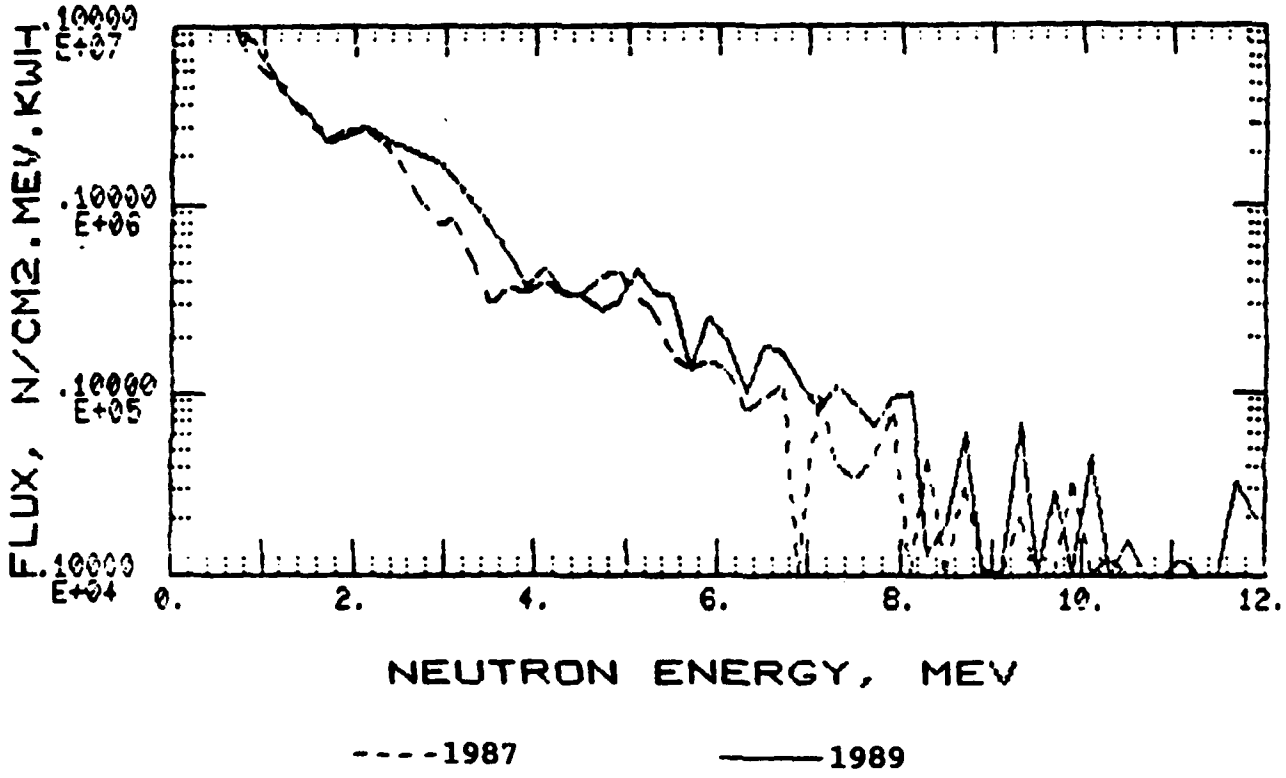



Figure 17: Comparison of the NE213 - measured neutron energy spectra (〉 600 keV) at the NATO standard reference point in 1987 and 1989. The 1989 measurements appear greater for 2 MeV - 4 MeV neutrons.

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Over the past few years the neutron (and to a lesser extent gamma-ray) energy spectra at the NATO standard reference point (400m from the core) at the Aberdeen Pulsed Radiation Facility, Aberdeen Proving Ground, MD, US has been the subject of experimental and theoretical controversy. This report describes the Canadian results of a joint NATO spectroscopic and dosimetric program carried out to end the controversy. Free-field and in-vehicle spectra are given, along with free-field and phantom dosimetric results. As a result of this work, several benchmark results have now been obtained, and specific recommendations for future research are given.

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